MiniBooster NEutrino Oscillation Experiment

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- Introduction
  - Motivation
  - Neutrino : Some History
    - Solar Neutrinos
  - ν- Oscillation : A brief Overview
- The MiniBooNE Experiment
  - The Detector
  - Physics Prospects
    - Oscillation Physics
    - Non-oscillation Neutrino Physics
- Beam Specifications for MiniBooNE
  - Impact of MiniBooNE on the Booster
  - Beamline to Target Station
  - Target Station and ν–beam
  - Radiation Issues
- Summary

MiniBooNE Collaboration

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Motivation

The MiniBooNE experiment is motivated by evidence of neutrino oscillations:

- **Observation of events by the LSND collaboration which are consistent with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.**

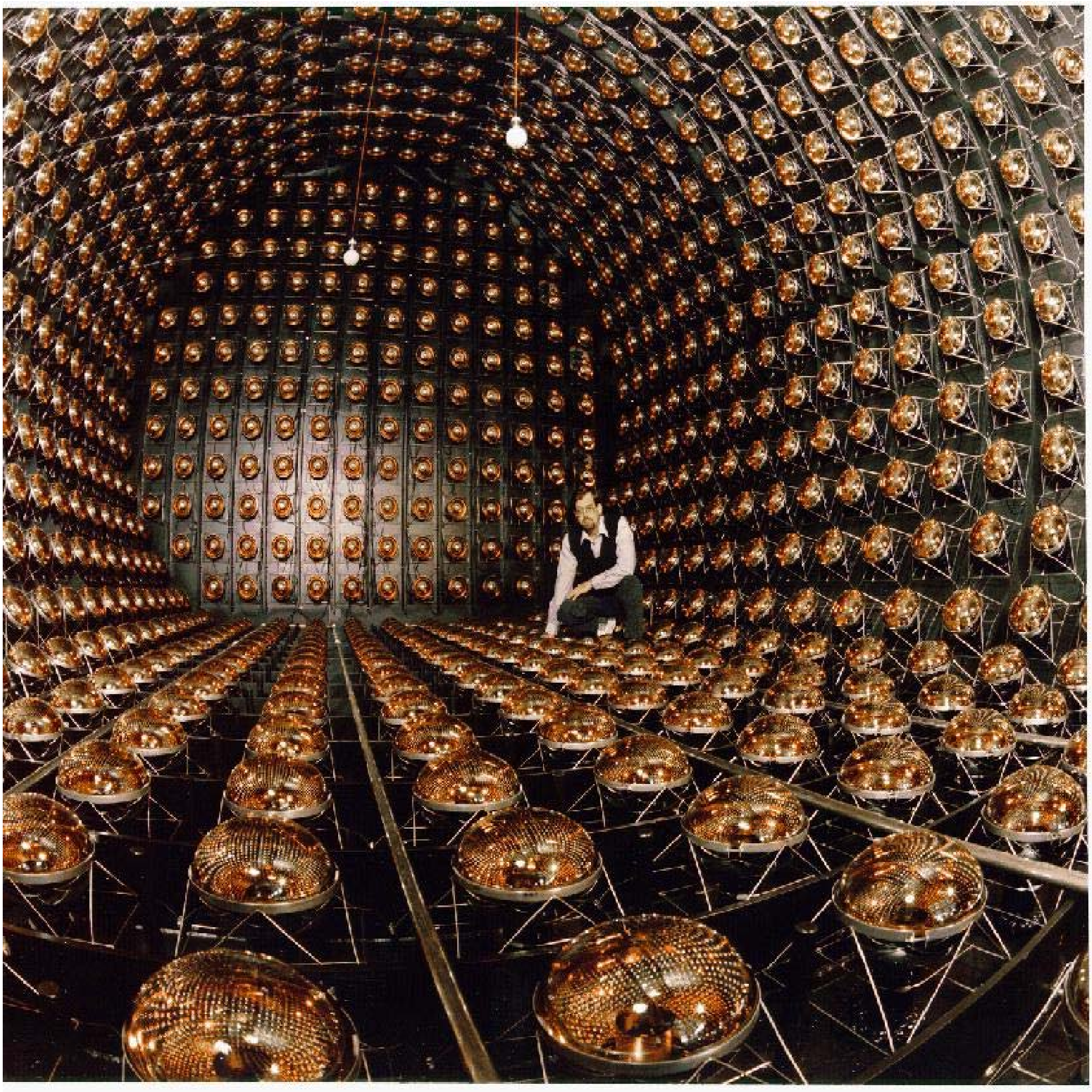
  The LSND experiment reported a signal excess of 82.8 ± 23.7 events which may be attributed to evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. [**PRL77, 3083 (1996) & PRC54, 2685 (1996), PRL81, 1774 (1998)**].

- **Observed deficit of the atmospheric ν_μ.**

  The Kamioka Collaboration, [**PL B280, 146 (1992)**] measures the ratio

$$\frac{(\mu / e)_{DATA}}{(\mu / e)MC} = 0.60^{+0.06}_{-0.05}(Stat) \pm 0.05(Syst)$$

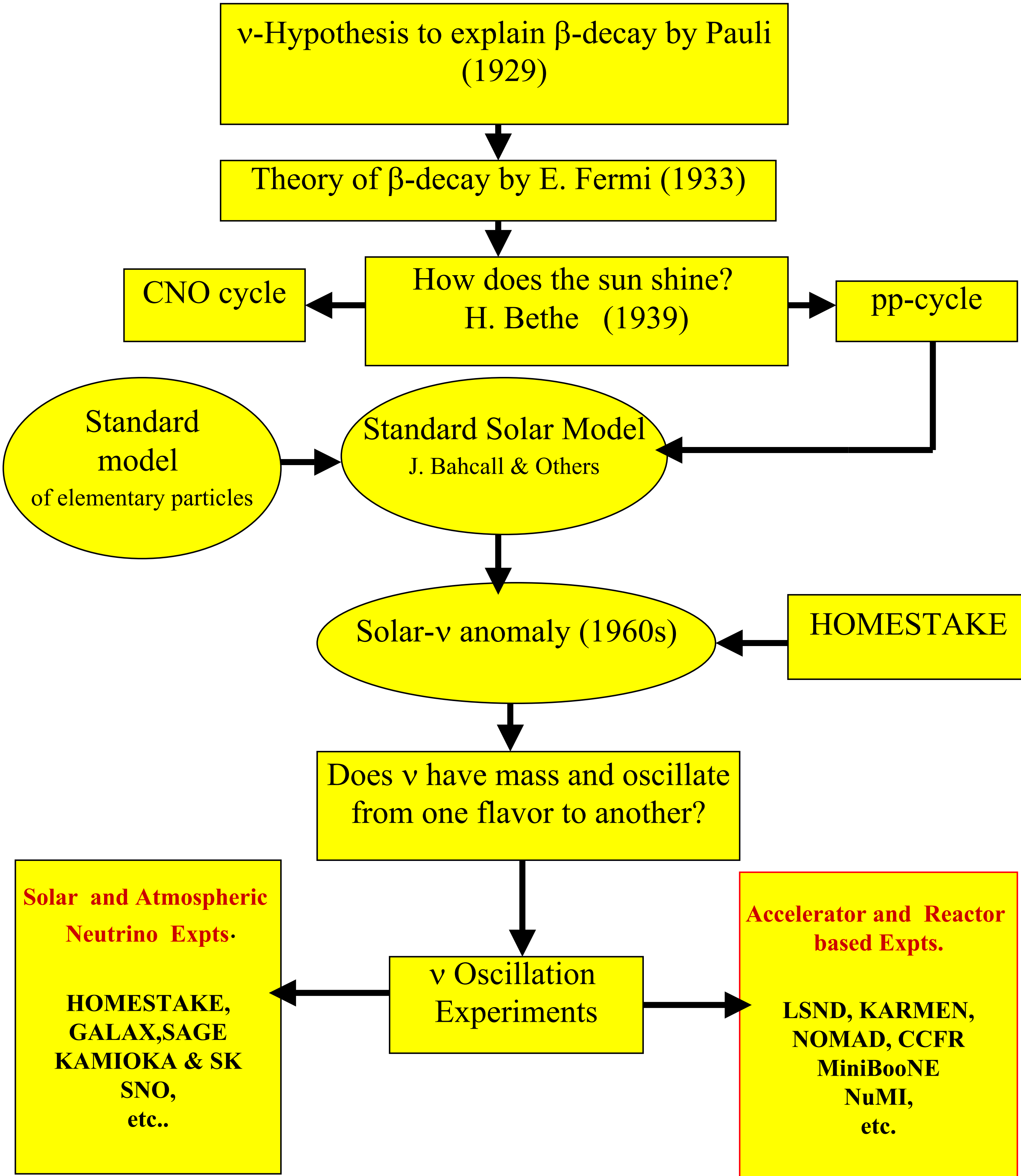
where the expected ratio is 1.0. From the Super Kamiokande experiment, the measured ratio is about the same within 12% .



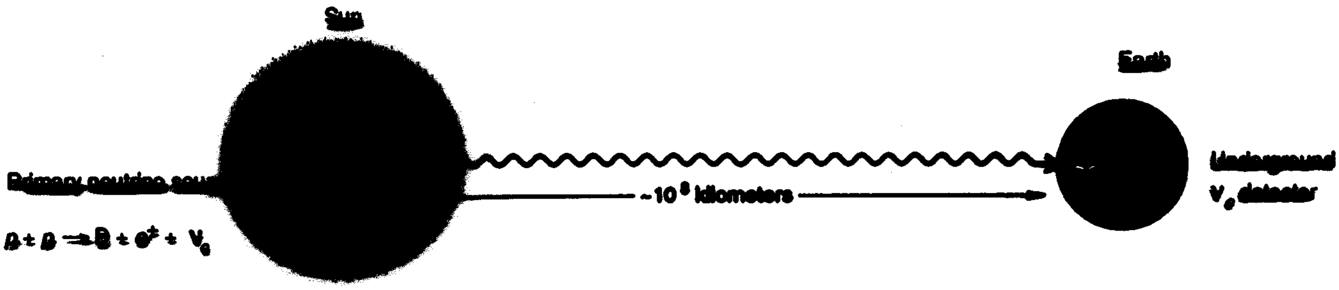
Chandra Bhat, BD Talk,
6/8/1999

Goal of the MiniBooNE experiment is to confirm or rule out the LSND results

Neutrino : Some History



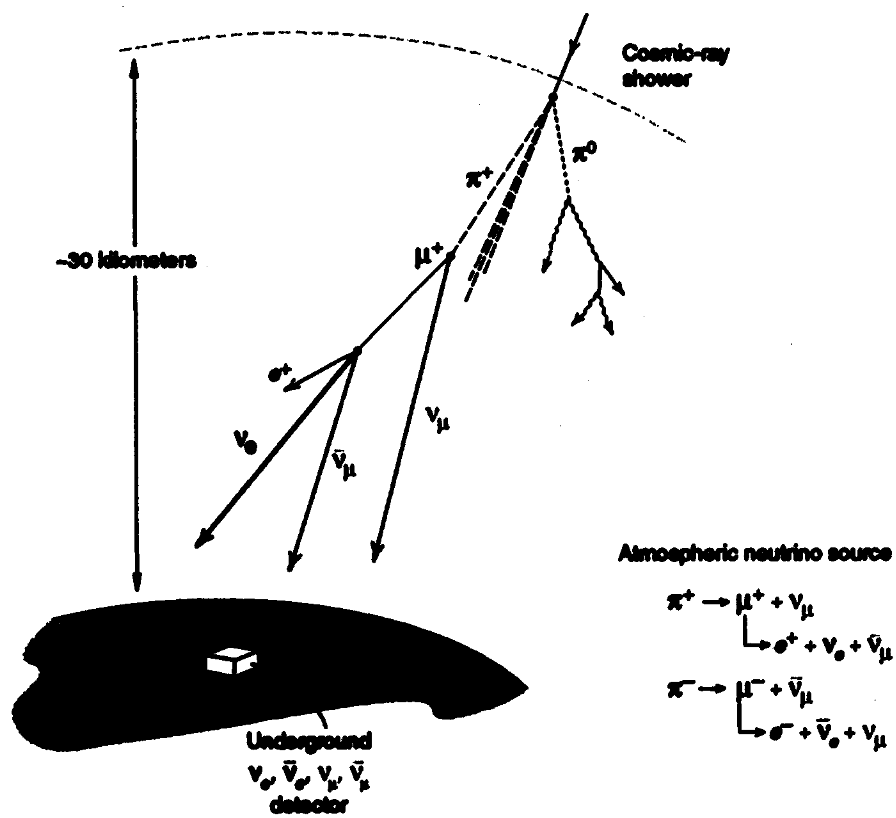
Chandra Bhat, BD Talk,
6/8/1999

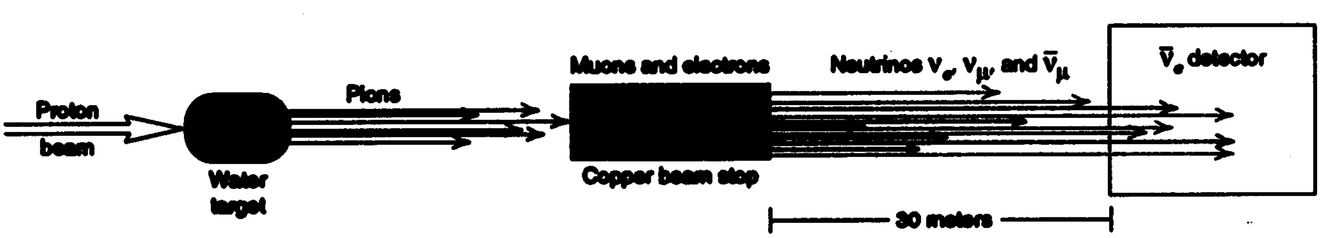


Other sources of neutrinos:

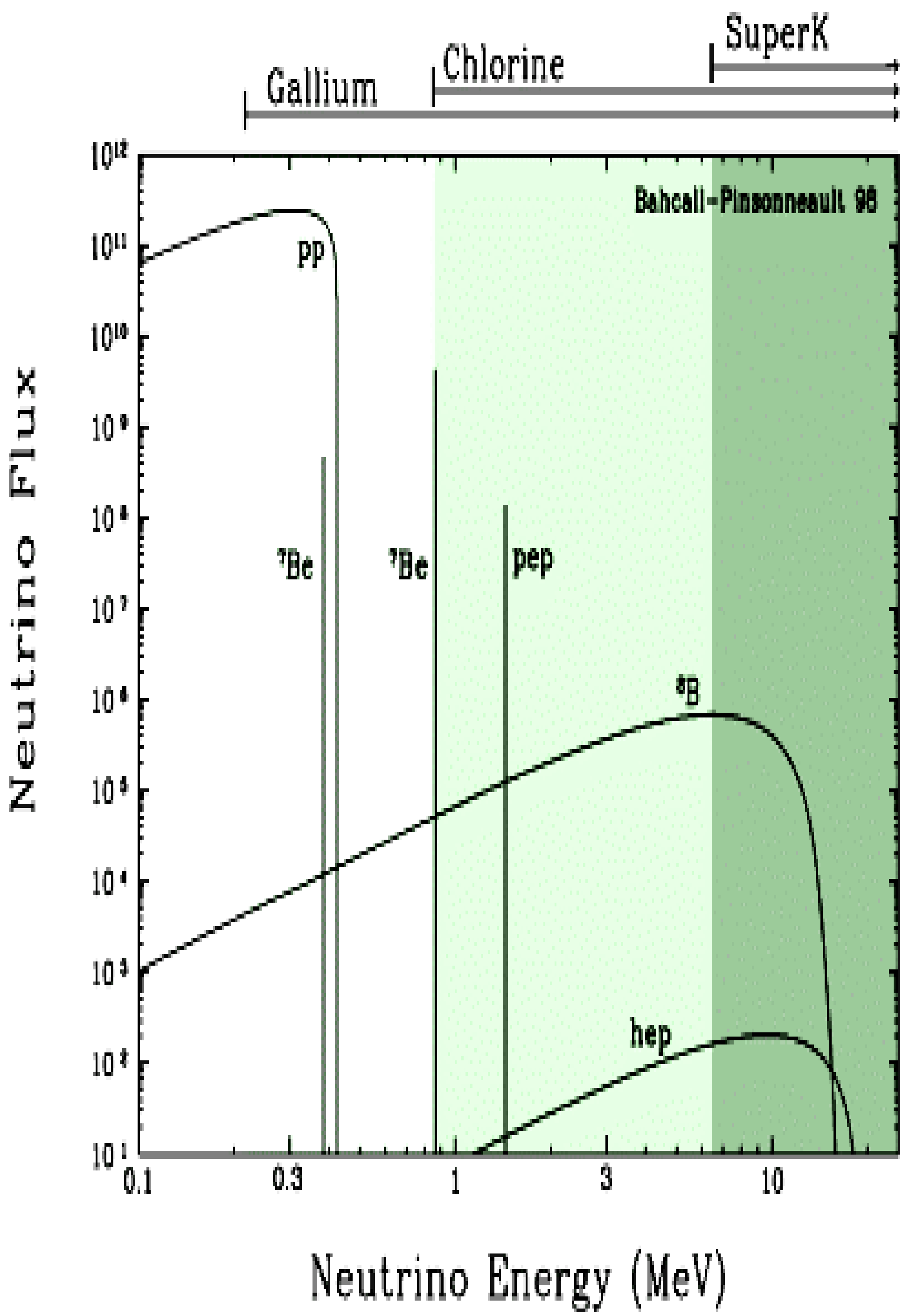
$e^- + {}^7Be \rightarrow {}^7Li + \nu_e$

${}^8B \rightarrow 2\,{}^4He + e^+ + \nu_e$





Solar Neutrino Spectrum



Flux at Eart
pp 6.0
^{7}Be 0.49
^{8}B 5.7x10
(10^{10} cm^{-2} s

Solar Neutrino Experiments

- Homestake

$$\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

$E_{th} = 0.814$ MeV

- SAGE and GALLEX

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

$E_{th} = 0.233$ MeV

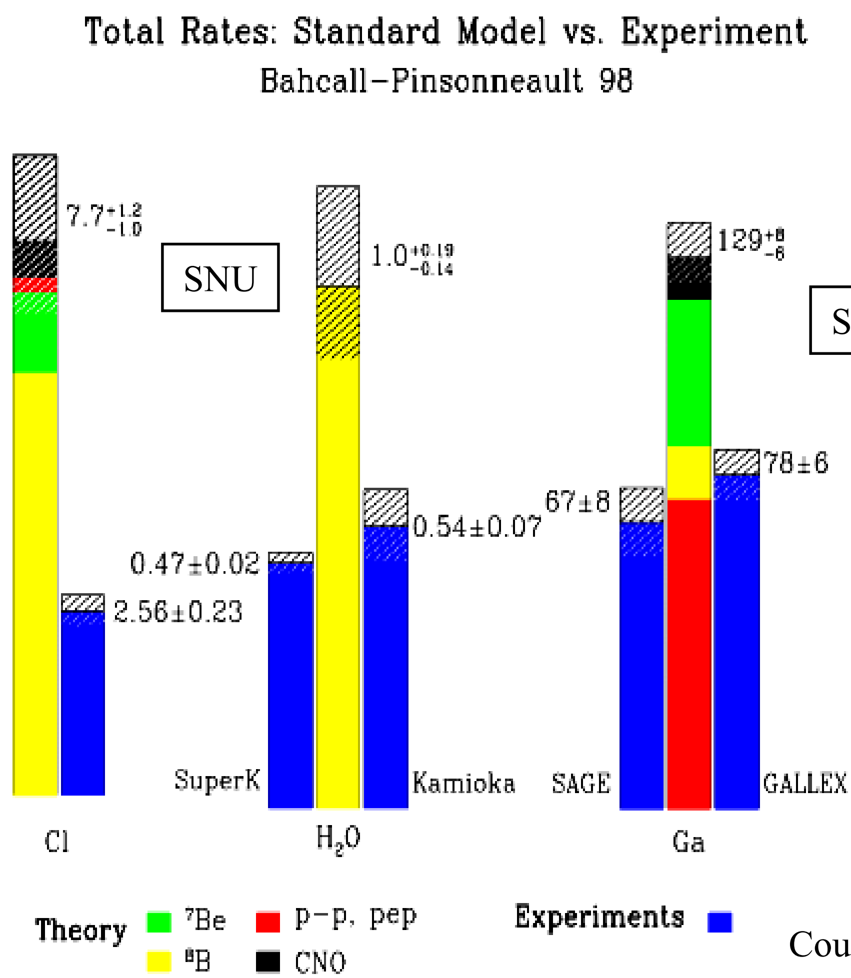
- Kamiokande +Super Kamiokande

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

$E_{th} = 6.5$ MeV

SNO(1999?),SuperKamiokande(1996-), BOREXINO(199?),ICARUS(2000), HELLAZ(200x)

Solar Neutrino Data 1998



Courtesy John Bahcall

Neutrino Survival Probability :

Electron neutrinos from the Sun seem to be lost en route to the Earth. The **neutrino survival probability**, P(E), is the probability that an electron neutrino created at the sun arrives at the earth.

Event Rates: Radiochemical Expts.

$$S_i = \sum_j \Phi_j \int_{Eth_i} \sigma_i(E_\nu)\varphi_j(E_\nu)p(E_\nu)dE_\nu$$

S_i Event rate in experiment *i*

Φ_j Total flux from neutrino source *j*

σ_i Cross section for experiment *i*

ϕ_j Normalized neutrino spectrum

p Neutrino survival probability

Event Rates: Kamiokande and SK

$$N(T) = n_0 \Phi_B \int_0^{t^{\max}(E_\nu^{\max})} dt\, R(T \mid t)$$

$$\times \int_{E_\nu^{\min}(t)}^{E_\nu^{\max}} dE_\nu \phi_B(E_\nu)\{p(E_\nu)\sigma_e(t, E_\nu) + [1 - p(E_\nu)]\sigma_\mu(t, E_\nu)\}$$

$$t^{\max}(E_\nu) = 2E_\nu^2 / (2E_\nu + m_e)$$

$$E_\nu^{\min}(t) = [t + \sqrt{t(t + 2m_e)}]/2$$

T measured electron K.E.
t true electron K.E.
R(T|t) resolution function

Modeling the Survival Probability:

Binned Method

: Radio-chemical Experiments :

$$S_i = \sum_k P_k \sum_j \Phi_j \int_{E_k}^{E_{k+1}} \sigma_i(E_\nu)\varphi_j(E_\nu)dE_\nu$$

Supe-Kamiokande Experiment :

$$S_i = \text{A complicated Expression}$$

C. M. Bhat, *et al*., PRL 81, 5056 (1998)

Modeling the Survival Probability:

Parametric Method

$$p(E_\nu \mid a) = \sum_{r=0}^{7} a_{r+1}\cos(r\pi E_\nu / L_1)/\{1+\exp[(E_\nu - L_1)/b]\}$$
$$+\sum_{r=0}^{3} a_{r+9}\cos(r\pi E_\nu / L_2)$$
$$L_1 = 2\ \text{MeV},\ b = 0.2\ \text{MeV}$$
$$L_2 = 20\ \text{MeV}$$

The first term models the high frequency components, which occur near the origin, while the second term models the lower frequency components.

Bayesian Analysis

$$P(a,\Phi \mid D,I) = \frac{L(D \mid a,\Phi,I)P(a,\Phi \mid I)}{\int_{a,\Phi} L(D \mid a,\Phi,I)P(a,\Phi \mid I)}$$

Take likelihood to be a multivariate Gaussian, ***I*** is prior info.

Marginalization

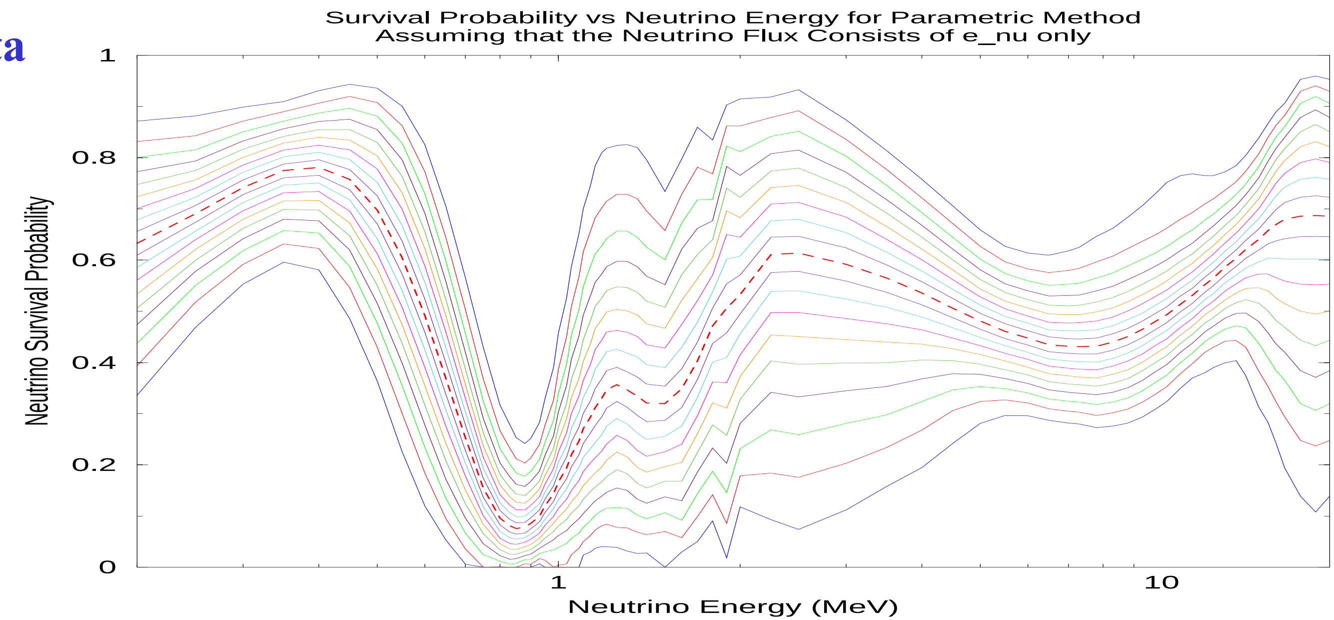
$$P(a \mid D,I) = \int_{\Phi} P(a,\Phi \mid D,I)$$

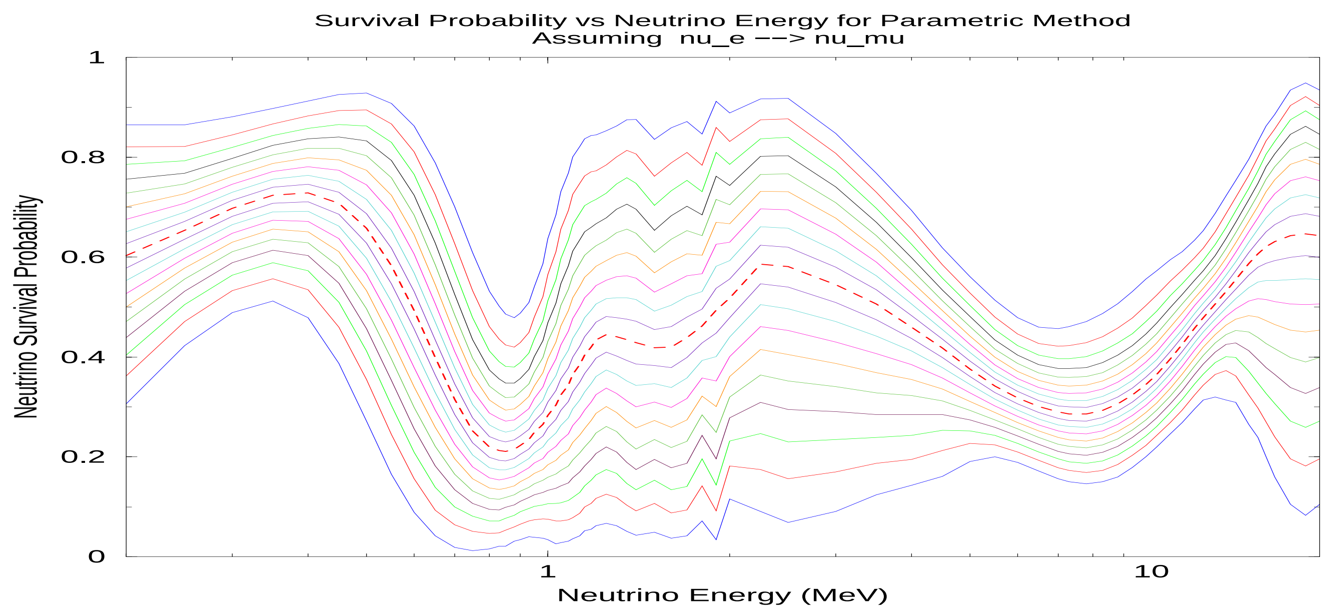
C. M. Bhat, *et al.*, PRL 81, 5056 (1998)

$$L(D \mid a,\Phi) = \exp[-\tfrac{1}{2}(D-Ba)^T \Sigma^{-1}(D-Ba)]$$
$$D = (S_1, S_2, N_1 \ldots N_{16})$$

$$p(E) = \int_a p(E \mid a)P(a \mid D,I)$$

* **1998 Solar-ν data and**
* **1998 SSM**





C. M. Bhat, *et. al.*, PRL, 81, 5056 (1998) and APS99 (Atalanta)

Neutrino Oscillations - a brief overview

For two family oscillations, take the mixing matrix to be:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

At production ($t = 0$:)

$$|\nu_\mu(0)\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

At a later time:

$$|\nu_\mu(t)\rangle = -\sin\theta e^{-iE_1 t}|\nu_1\rangle + \cos\theta e^{-iE_2 t}|\nu_2\rangle$$

And the $\nu_\mu \leftrightarrow \nu_e$ oscillation probability is:

$$\begin{aligned} P_{osc} &= |\langle\nu_e|\nu_\mu(t)\rangle|^2 \\ &= \frac{1}{2}\sin^2 2\theta[1 - \cos(E_2 - E_1)t] \end{aligned}$$

Use $E_1 = \sqrt{p^2 - m_1^2} \approx p + m_1^2/2p$ (and same for E_2) and $(t/p) = (tc)/(pc) = L/E$

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

Neutrino Oscillations - a brief overview

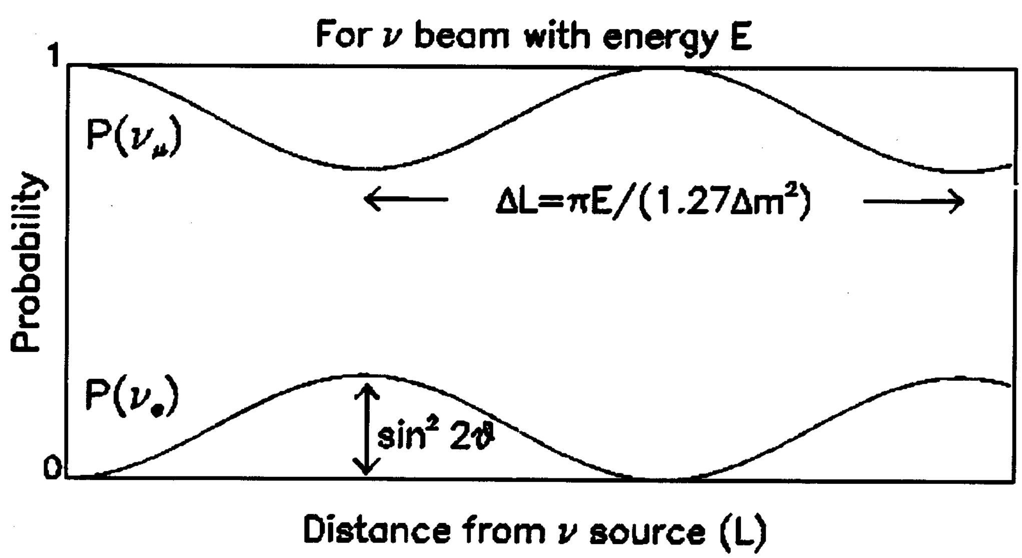
$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

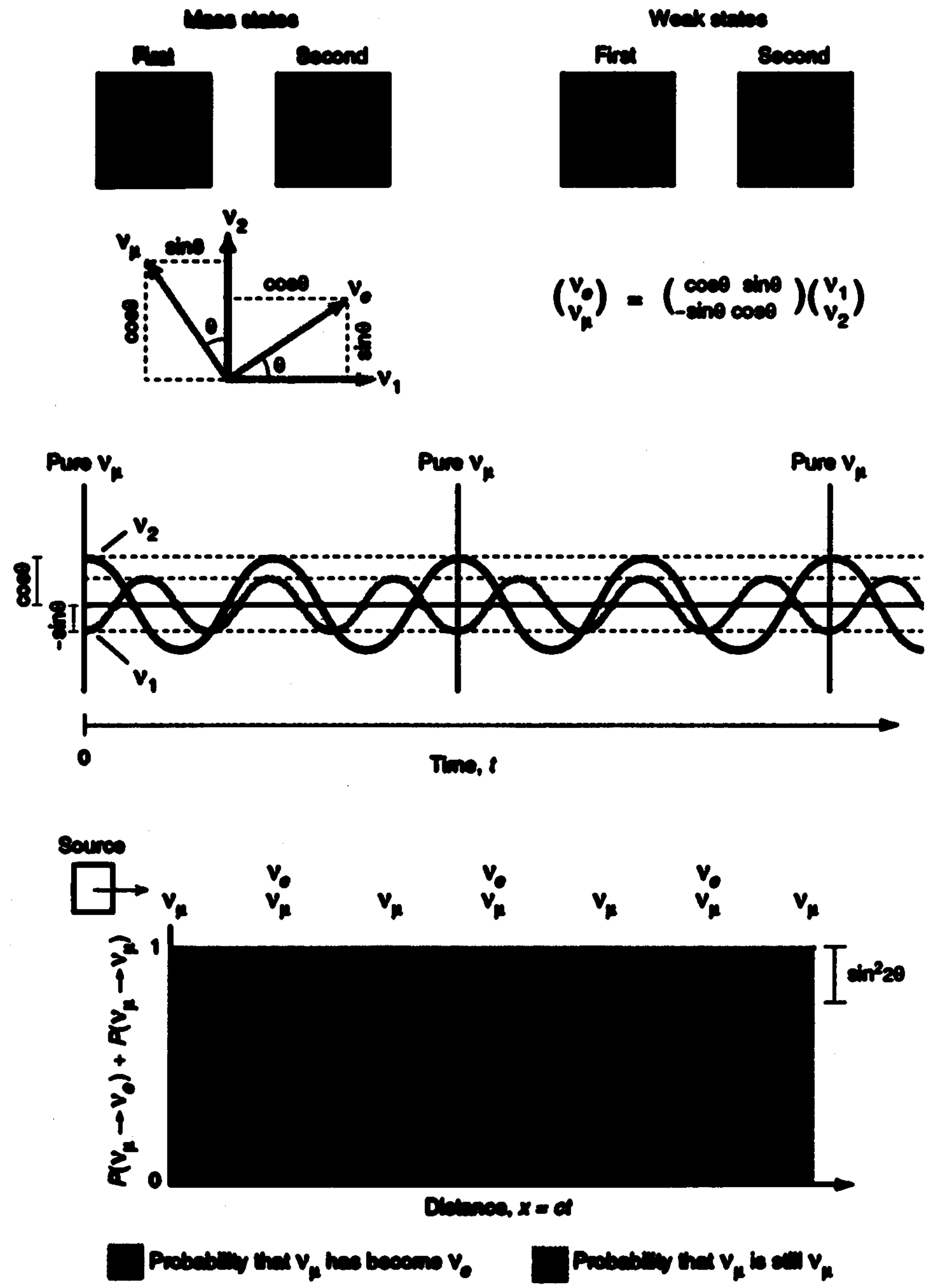
P_{osc} depends upon two experimental parameters:

- L – The distance from the ν source to detector
- E – The energy of the neutrinos

And P_{osc} depends on two fundamental parameters:

- $\Delta m^2 = m_1^2 - m_2^2$
- $\sin^2 2\theta$





$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

The MiniBooNE Experiment

- **MiniBooNE is a Short-baseline neutrino oscillation experiment, which will use ν's created using the protons from the Booster.**

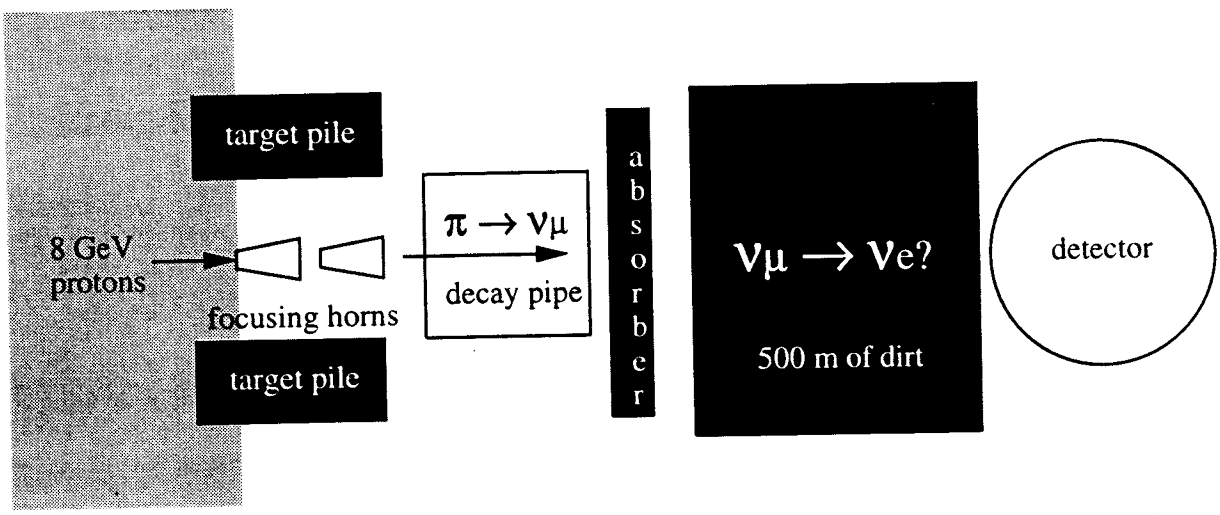
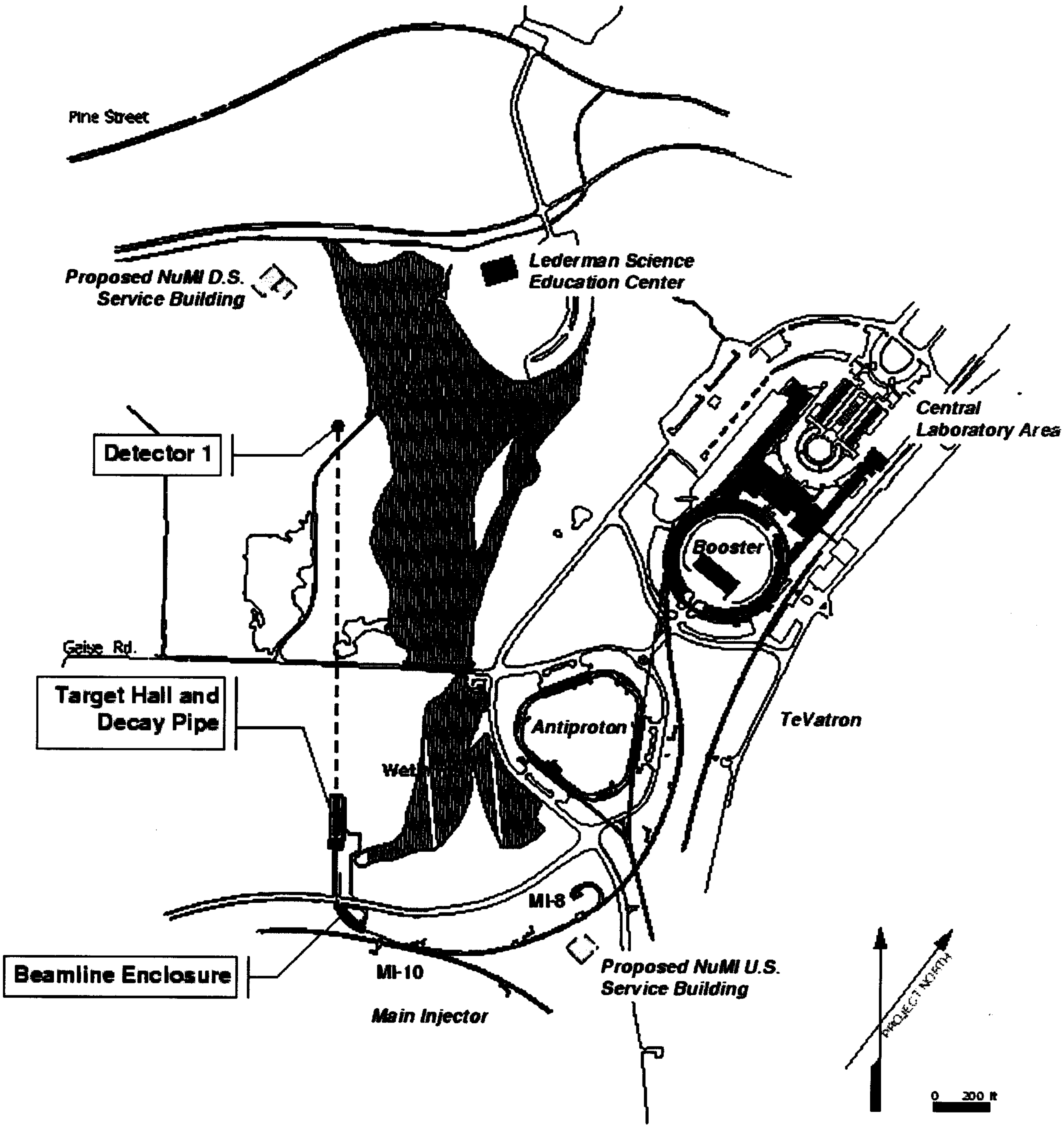


Figure 2.1: An overview of the MiniBooNE Projects showing the portion described in Chapter 2 by the shaded area.

The MiniBooNE Site



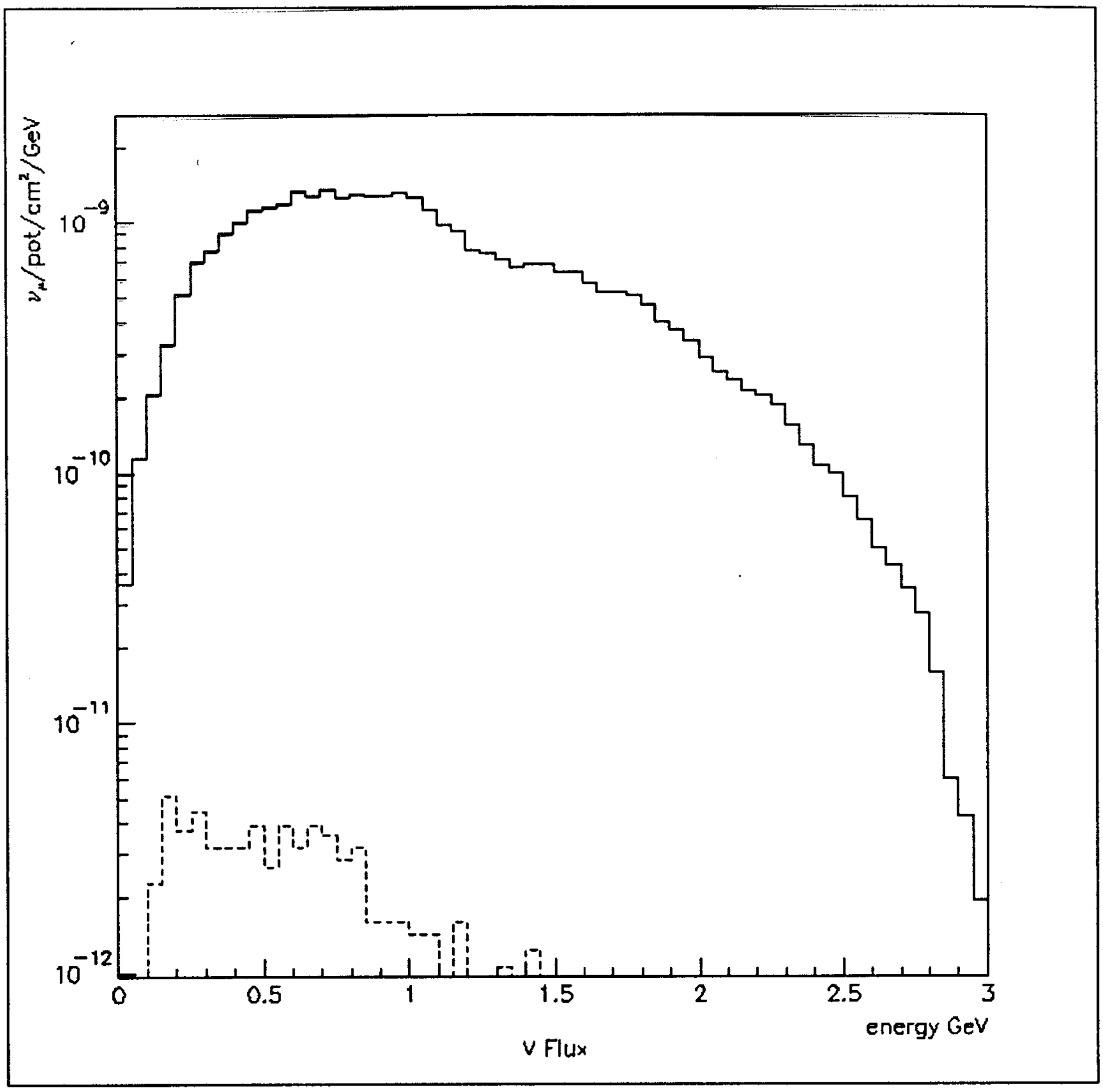


Figure 4.3: The ν_μ flux (solid) for the MiniBooNE two–horn system compared to the ν_e background (dashed).

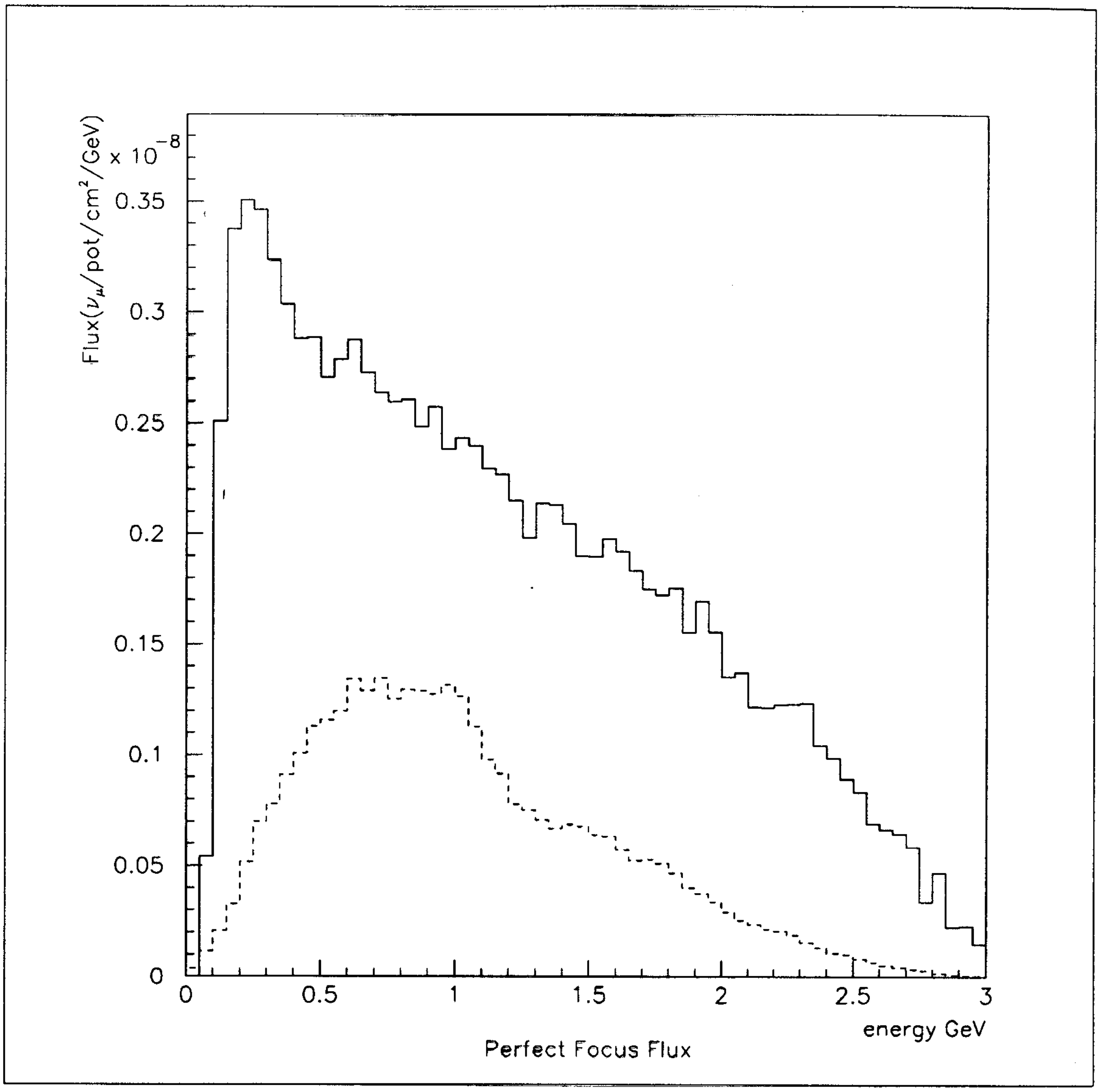
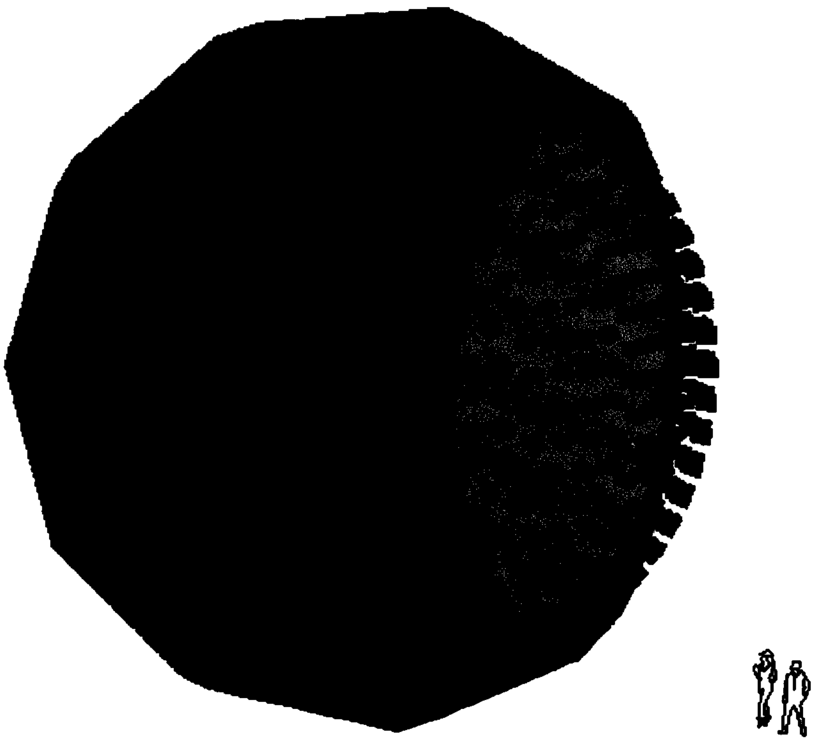


Figure 4.2: The ν_μ flux for the MiniBooNE two–horn system compared (dashed) to perfect focusing (solid).

The MiniBooNE Detector Tank

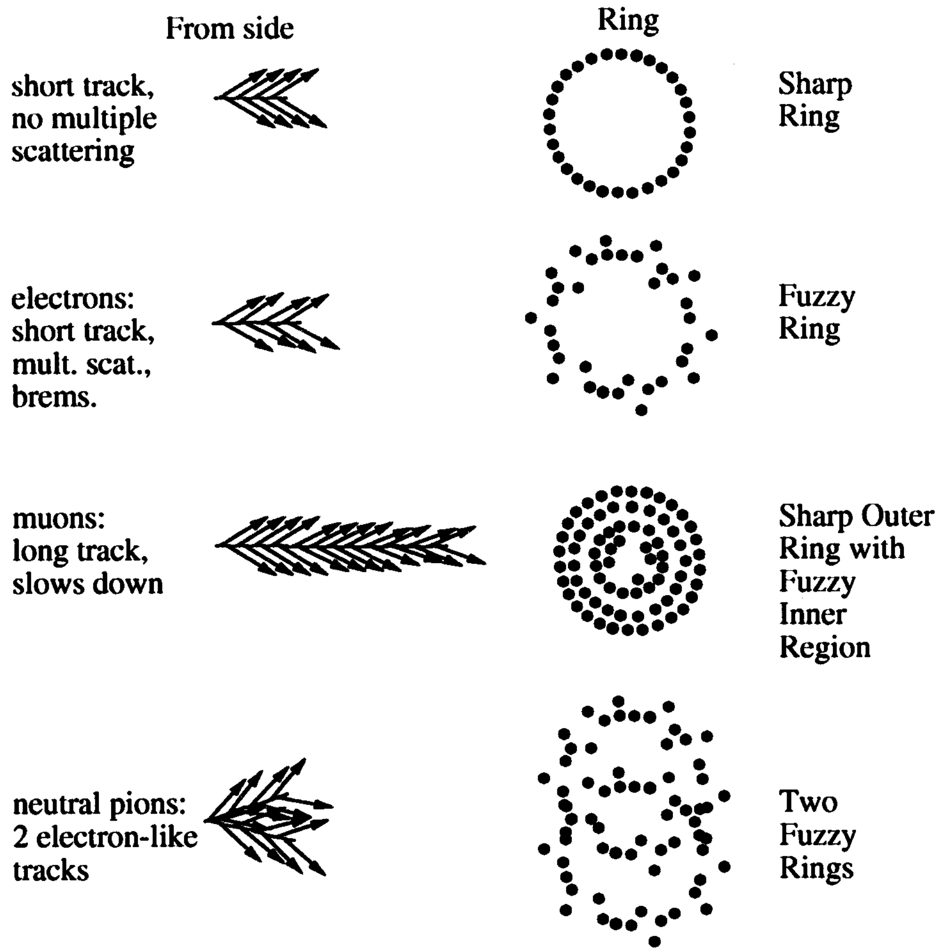


- 1280 phototubes in detector located at 5.75m radius, and 240 phototubes in veto
- Fiducial volume: 445 tons (5.75m radius sphere)
  Total volume: 807 tons (6.1m radius sphere)
- Pure mineral oil in detector & veto
- Opaque shield between veto and detector region.

The basics of particle identification...

Cerenkov Light:

Prompt signal in the form of rings



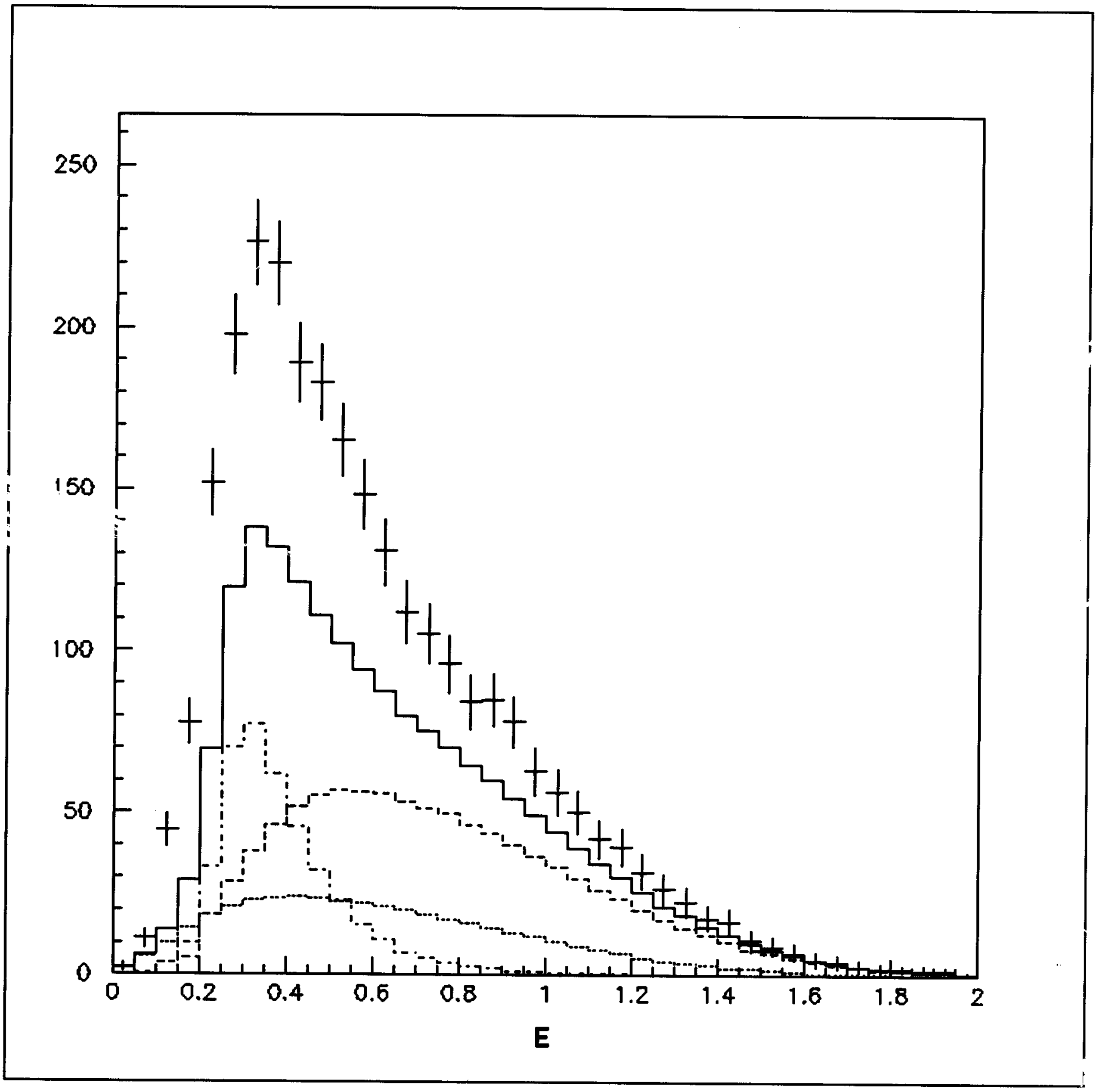
Scintillation Light:

Later signal and isotropic

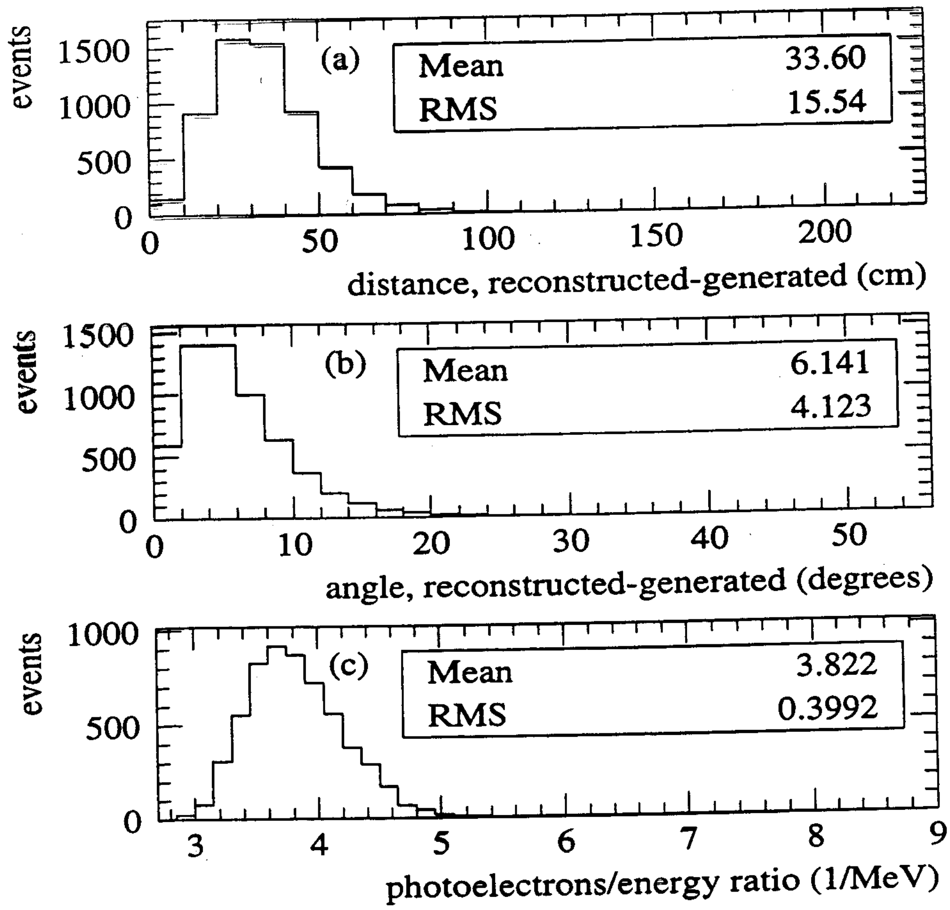
Visible Energy Distribution for Oscillations at
$\Delta m^2 = 0.4$ eV^2 , $\sin^2 2\theta = 0.02$

+ signal & background
– total background

–.– π^0 background
––– ν_e background
...... μ^- background



Electron Resolutions



For ν_eC interactions, the (top) position, (middle) angular, and (bottom) energy resolutions for a large sample of electrons generated in the tank by the detector simulation.

Estimated Signal

After running for 1 year (2×10^7s, 5×10^{20} pot)...

- $\nu_\mu \; C \rightarrow \mu^- \; N$ 700,000 events

  Assuming 50% electron ID efficiency and 100% $\nu_\mu \rightarrow \nu_e$ transmutation then...

- $\nu_e \; C \rightarrow e^- \; N$ 400,000 events

  If $\Delta m^2 = 0.4\text{eV}^2$ and $sin^2 2\theta = 0.02$ then

- $\nu_e \; C \rightarrow e^- \; N$ 960 events
- Intrinsic ν_e 960 events
- μ^- Misidentification <400 events
- π^0 Misidentification 400 events

Methods for Testing a Signal

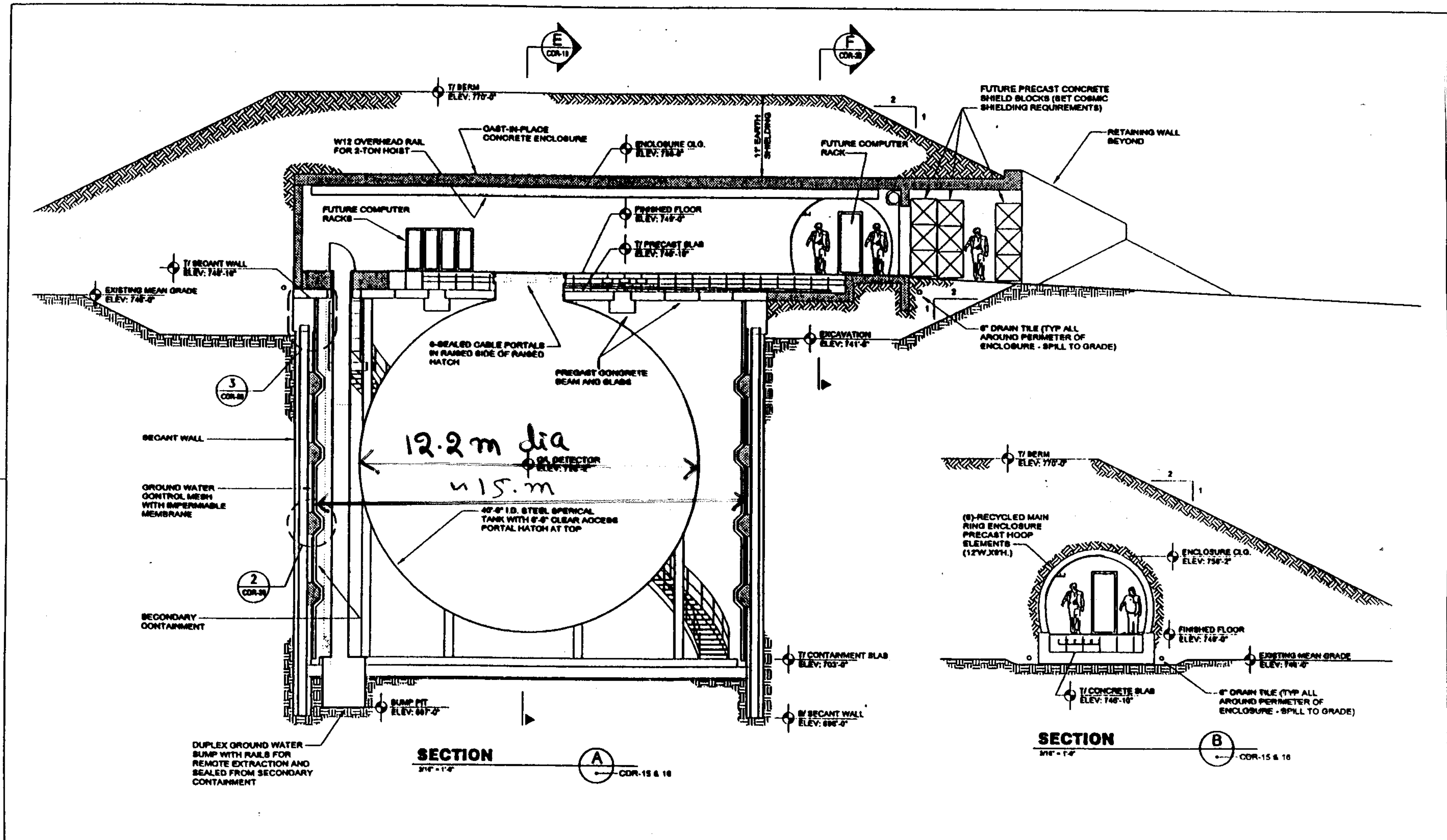
- Vary meson decay length from 50 m to 25 m

Example: assume a 600 event excess after 2.5×10^{20} p.o.t.:

Decay Pipe Length (m)	ν_μ events	$\nu_\mu \rightarrow \nu_e$ (oscillation events) $\propto L_{decay}$	if due to ν_e bkgnd: $\pi \rightarrow \mu \rightarrow \nu_e \propto L^2_{decay}$ K decays constant
50	700,000	600 ± 50	600 ± 50
25	390,000	334 ± 35	174 ± 32

- Run with an antineutrino beam
- Modify the horn system to vary neutrino energy. Not easily done!

- Build a second detector ... BooNE!



REV.	DATE	DESCRIPTIONS
		REVISIONS

	NAME	DATE
DESIGNED	TIM BURKE	
DRAWN	TIM BURKE	
CHECKED		
APPROVED		
SUBMITTED		

SCALE:

3/16" = 1'-0"

FERMI NATIONAL ACCELERATOR LABORATORY

UNITED STATES DEPARTMENT OF ENERGY

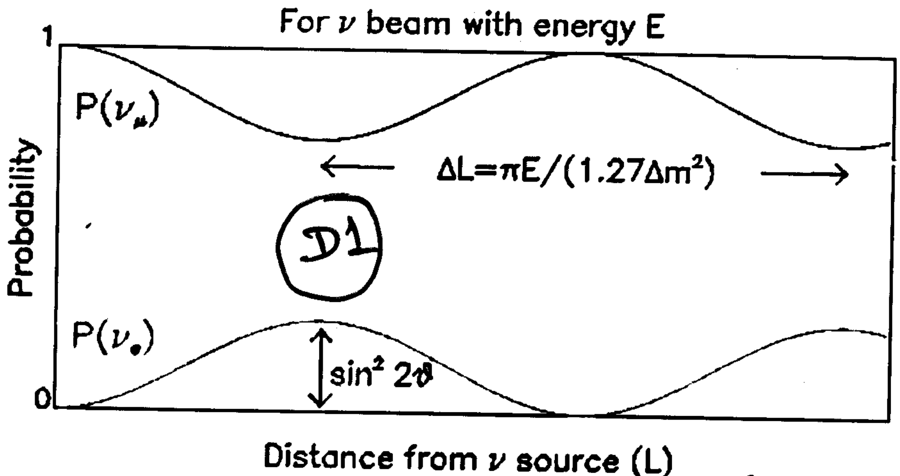
MINI-BooNE

DETECTOR SECTIONS

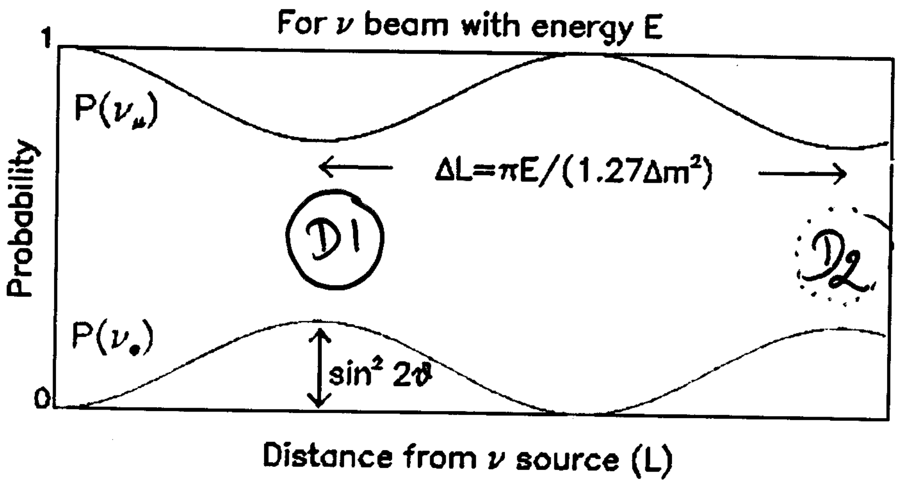
DRAWING NO. 6-7-52 CDR-17 REV

The MiniBooNE Experiment

- This program has **two phases**:
  - MiniBooNE - Single detector experiment

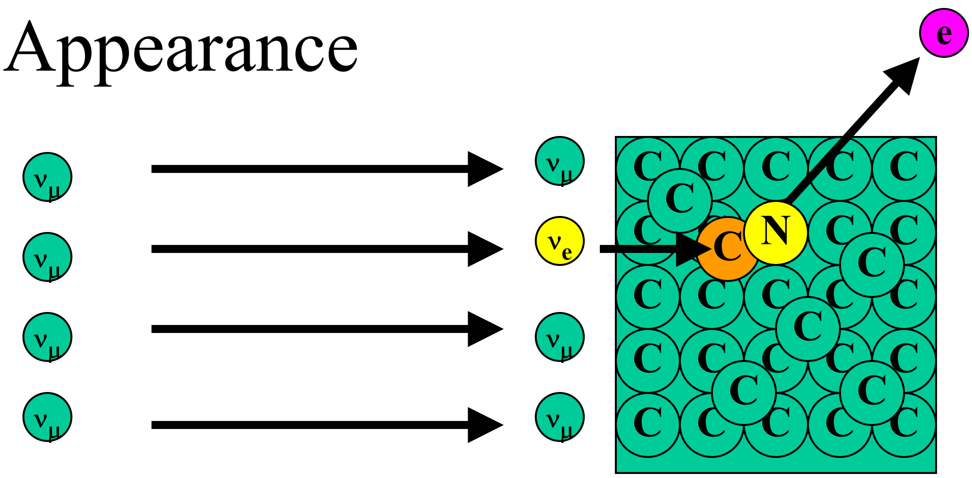


  - BooNE - two detectors experiment to make precision measurements.



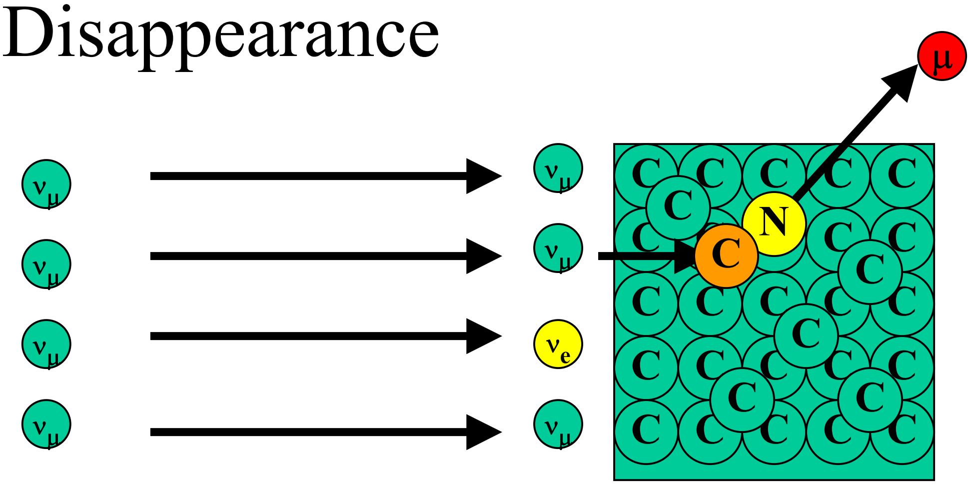
The MiniBooNE Experiment
Signatures

- Appearance



1000 Events/y

- Disappearance

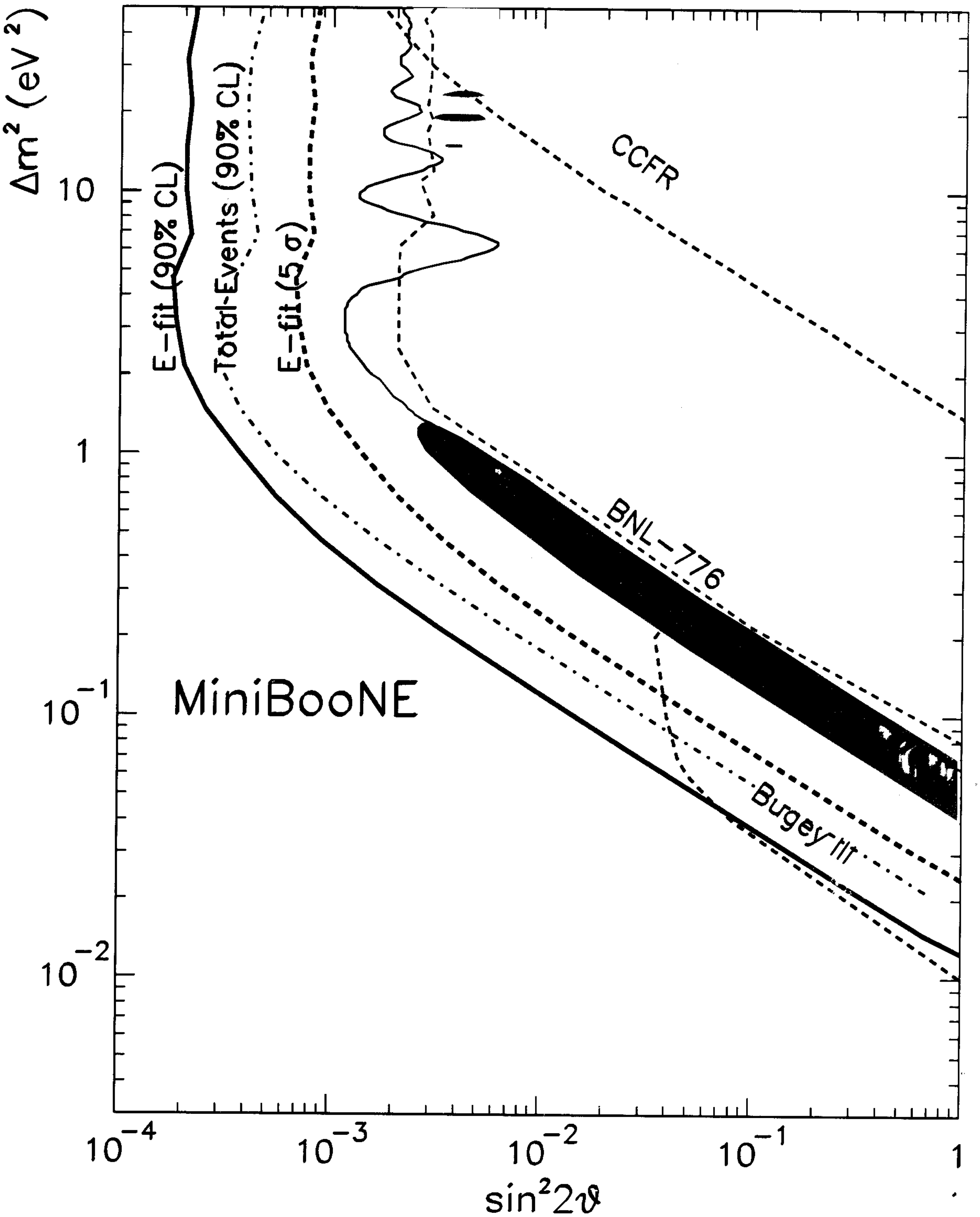


500k Events/y

- In addition, if neutrino oscillations are observed, the experiment will be able to measure Δm^2 and $\sin^2 2\theta$.

Estimated confidence level limits MiniBooNE will reach in one year of running

with 5×10^{20} p/year on the target -



Non-Oscillation neutrino Physics

- Neutrino-nucleon elastic scattering

$\nu_\mu + N = N + \nu_\mu$ **72k events**

offer the possibility of extracting Gs, the strange quark axial form factor of the nucleon

- Neutrino charged-current scattering

$\nu_\mu + {}^{12}C = {}^{12}N + \mu^-$ **510k events**

$\nu_\mu + {}^{12}C = {}^{12}B + \mu+$ **150k events**

will be measured to high precision.

- Neutral current π^0 production

$\nu_\mu + {}^{12}C = X + \nu_\mu + \pi^o$

65k events

is a sensitive probe to structure of the weak neutral-current.

- Neutrino-electron neutral -current scattering

$\nu_\mu + e^+ = e^+ + \nu_\mu$ **130 events**

get infornation on Neutrino-electron neutral -current scattering.

Neutrino Beam Specifications

- To get 1000 oscillation signals/year the MiniBooNE calls for
  - A high intensity wide-band ν_μ -beam with **E_ν ~0.5 –1.0 GeV**
  - **L~500 meter**.
- Keep ν_e background as small as possible.
- Long-term reliability
  - Accelerator performance
  - Beamline alignment
  - Mechanical stability
- Use Booster protons to produce the neutrino beam:
  - Energy of the proton beam is 8 GeV
  - 5×10^{12} ppp with 2×10^{20} p/y.
  - 5 Hz
- Personnel Safety

Advantages with the Booster Beam

- Low cosmic ray background, because the beam pulses are 1.6 μsec long.
- Energy of the primary beam is exactly equal to ten times that of the LSND beam energy. Hence, L can be selected so that the facility fits on the Fermilab site.
- The Linac and Booster are very reliable accelerators.

Impact of MiniBooNE on Booster

- **Protons per pulse : 5 x 10^{12}** (This has been achieved; special thanks to Ray Tomlin and other Booster and Linac Group members).
  - Acceleration efficiency needs to be improved.
  - Reproducibility is an issue that is being addressed.

    Does not appear to be a problem

- **Compatibility with Run II**
  - During Collider Run II, the Booster beam is needed once every 1.5 sec for pbar production, which is the dominant mode of use. For the rest of the time the Booster can be used for MiniBooNE experiment.

    Hence, this is not a problem.

- **Booster Rep Rate Need to be 7.5 Hz to Accommodate Run II, MiniBooNE and NuMI**.
  - Booster and Linac are traditionally very reliable machines (past experience is 3.3% DT). However, high rep-rate and high intensity calls for improvements of the Booster RF system.

    This needs some work but is doable.

- **Protons per hour = 1.1x 10^{17}**
  - Needs significant amount of work; extraction losses at Long 3 limits the Booster to 5x 10^{15} pph. **This needs to be improved by a factor of 20!**

1.1x 10^{17} pph from the Booster !

To achieve this, the following problems need to be addressed

- **The extraction losses under West Booster Tower** : These losses can be eliminated by putting a notch in the beam. Up to a factor of 10 reduction in loss is already observed with about 5 bucket notch. Further improvements are needed.
- **Badly located preferred loss points**: Now the losses are showing up at Long 4. The reasons are not well understood. Reduce losses by locally increasing aperture with magnet moves.
- **Transition losses** : $\gamma_t -$ jump, which exists. More work on damper systems is needed.
- **Up to 30% beam loss during the early part of the acceleration cycle** : Needs accelerator studies: Space charge effects and/or capture efficiency.

Some progress have been made in Booster; further Booster improvements are needed.

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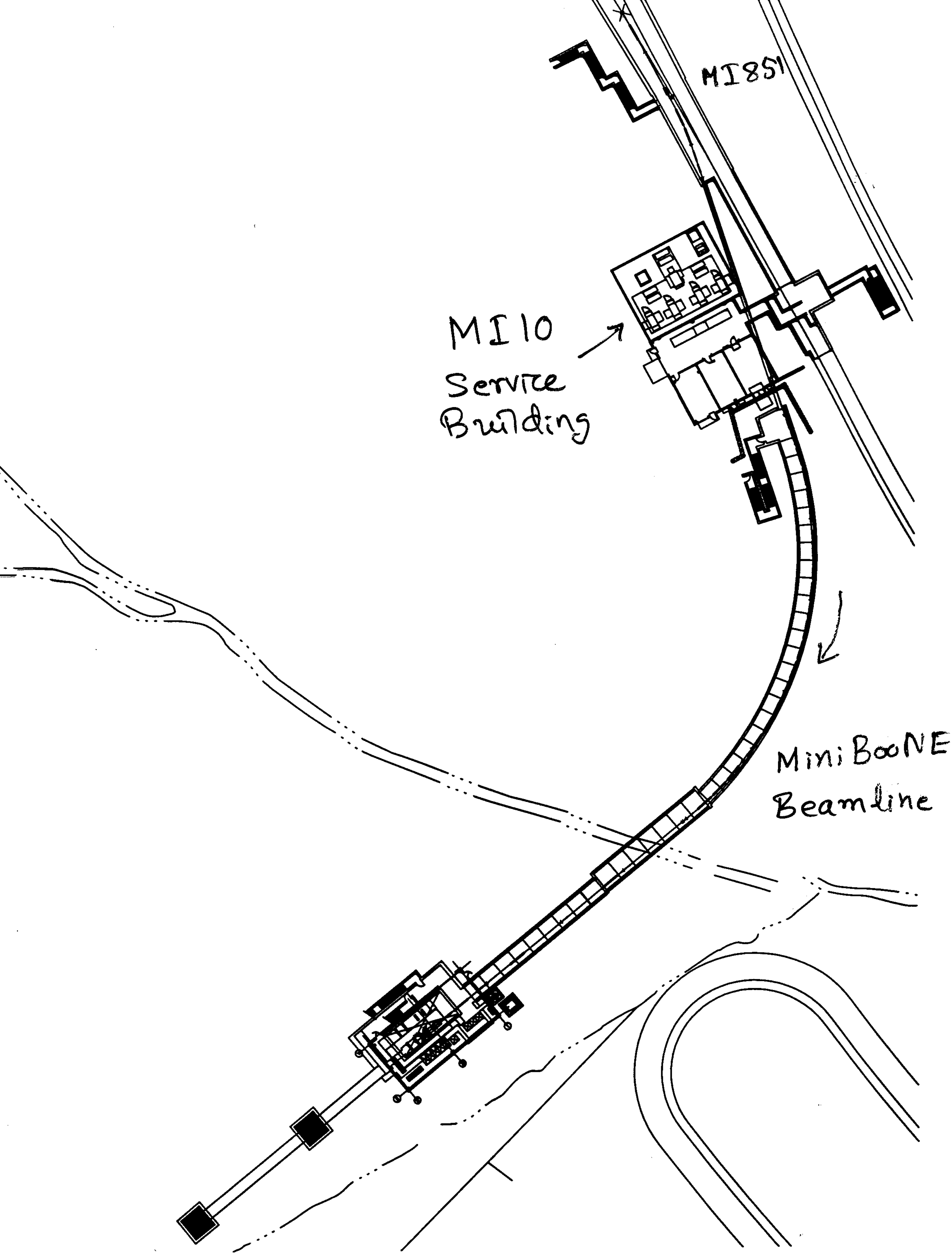
Beamline to the Target Station

- Beamline to the MiniBooNE Target Station should meet the following requirements :
  - Beam position stability on target < 1 mm.
  - Targeting angle stability < 4.6 mradian.
  - Beam spot 1/2 size < 5 mm.
- To meet these requirements a beamline with 40π admittance has been designed. It consists of two parts:
  - Existing MI8 Beamline
  - A new Beamline from MI851 to the MiniBooNE target station

    This beamline is designed using
    - **Nineteen EPB Dipoles**
    - **Two 3Q52, One 3Q120, Six 3Q60 Quadrupoles**

      All running at a constant current
    - **14 Permanent magnet quadrupoles**



MI851
MI10
Service
Building
MiniBooNE
Beamline

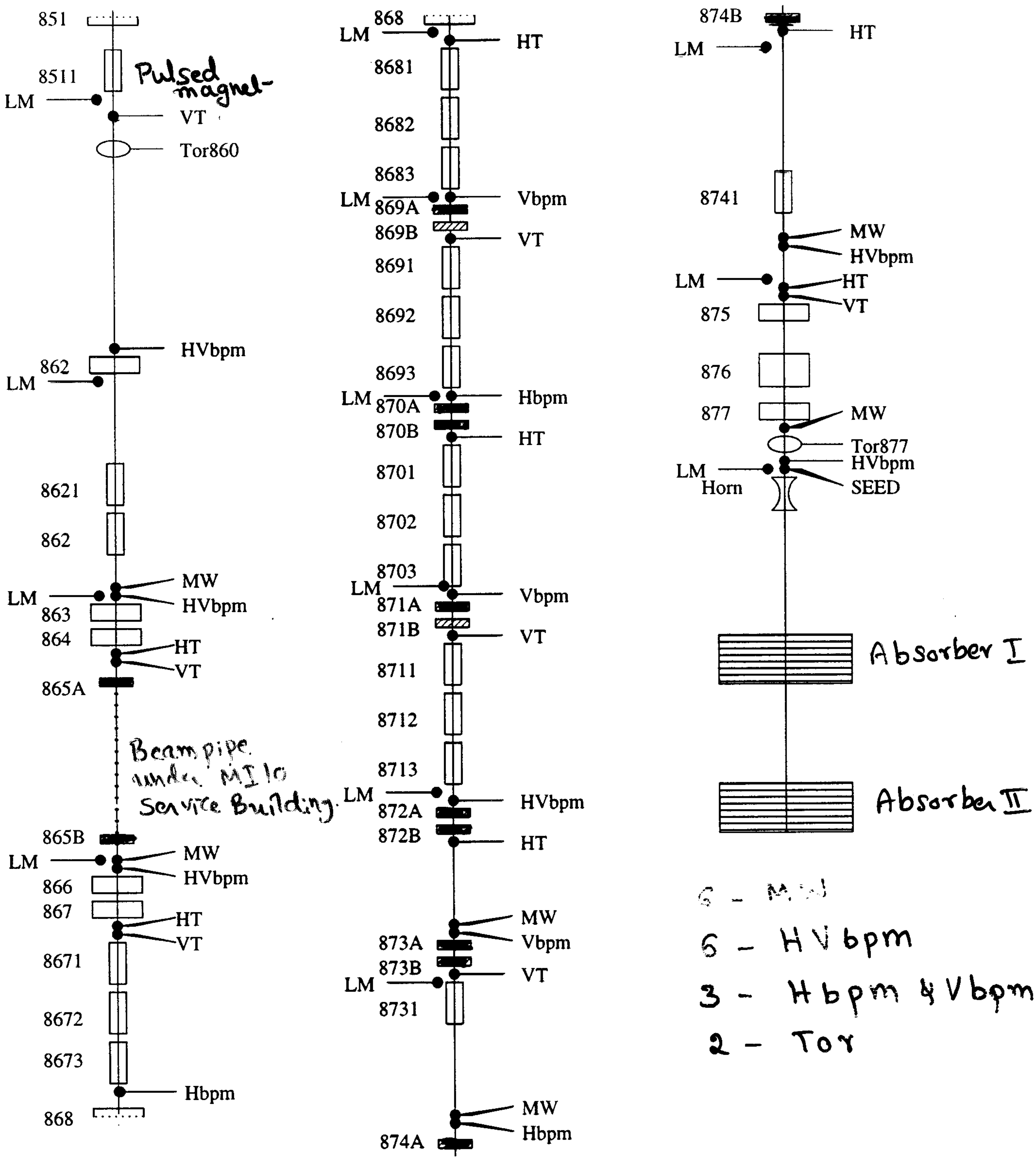


Figure 2.10: Schematic overview of location of instrumentation in the primary proton beamline. Key LM: – loss monitor, VT – vertical trim, HT – horizontal trim, MW – multiwire, Tor – toroid, bpm – beam position monitor.

Target Station and ν–beam

- The Target station and ν-beam consist of four parts:
  - **Target Hall & Target Pile** : The target hall design for the MiniBooNE neutrino beam is based on the PBAR Target Hall. The dimension of the target pile is optimized to provide adequate shielding in compliance with EPA and DOE limits for GW and SW.
  - **Focusing system** : MiniBooNE is a **two-horn** system. **The target is part of the first horn**.The parameters like **size, shape, length and current** for each horn is optimized to maximize the ν-flux at the ν-detector.
  - Decay Region : This is a **1 m (r) 50 m (L)** pipe with a gap for a **movable absorber at 25 m**.
  - Beam absorber : The absorbers remove secondary hadrons and low energy muons. There will be **two water cooled absorbers** each **12ft (H) x10ft (W) x 10ft (L).**

Radiation Safety Issues

- There are **six radiation safety issues** in the design of the MiniBooNE Experiment
  - Prompt Radiation
    - Accidental Beam Loss
    - Normal Beam Loss
  - Residual Activity of Irradiated Beam Line Elements
  - Ground and Surface Water Activation
  - Air-Borne Activity
  - Muons

We have used the Monte Carlo codes MARS and the CASIM to address the above issues.

Radiation Safety Issues (cont.)

- Prompt radiation is of concern only under **Beam-On** conditions. The main contribution is from : **n, μ, γ** produced during interactions.

Dugan's Criteria for MiniBooNE : N_p = 9E16 p /hr

	Over the Magnet	over the beam pipe	Buried beam pipe
Prompt Radiation:			
D<1mr/acc.	25.1 ft	21.9 ft	27 ft
D<5 mr/acc.	23.5 ft	20.4 ft	25 ft
D<100mr/acc.	19.7 ft	16.7 ft	21 ft
E-Berm : For Beamline			
2% Beam loss	20.1 ft	16.9 ft	21.5 ft
10%Beam loss	22.21 ft	19 ft	23.6 ft

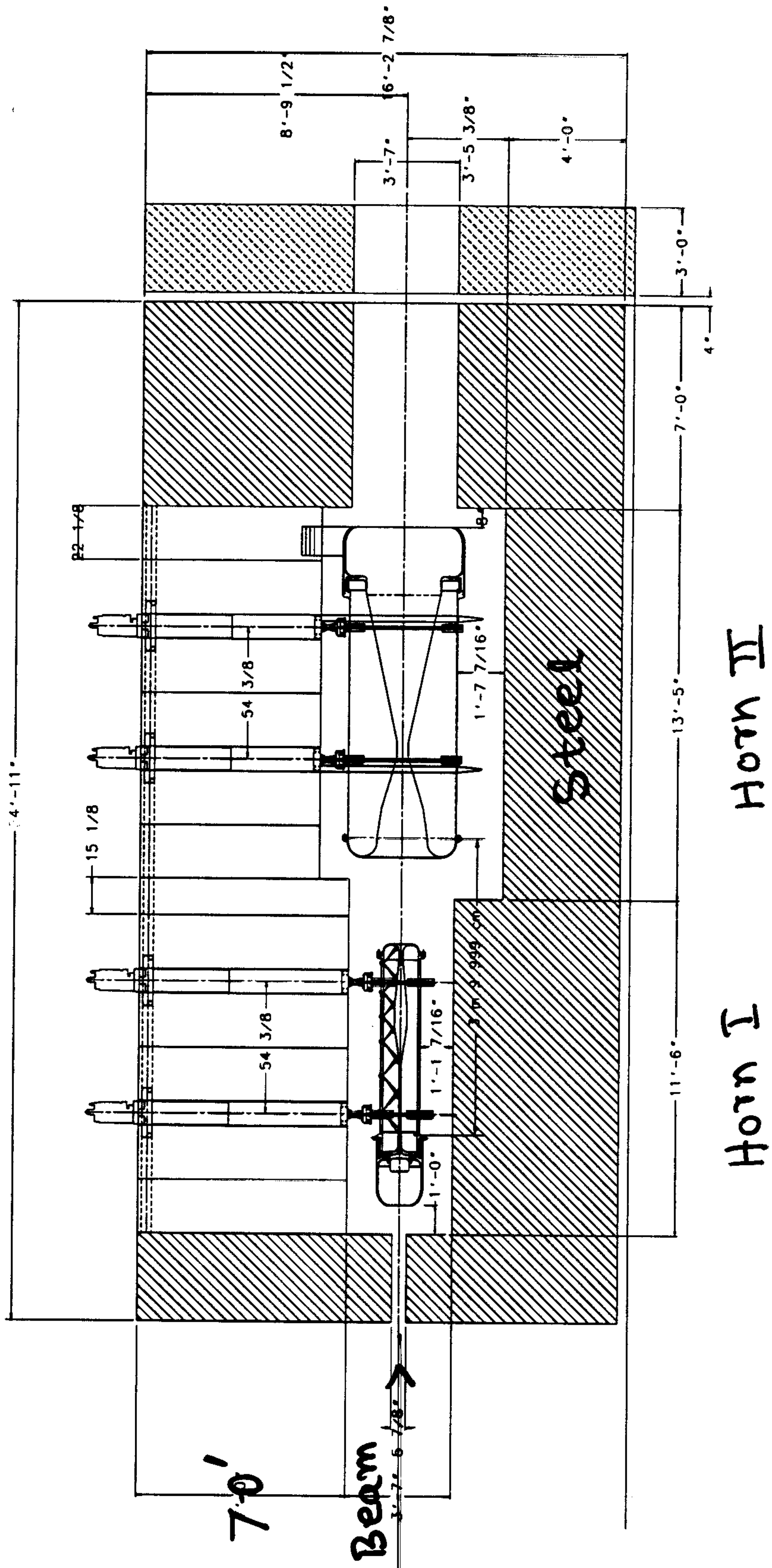


Figure 3.9: An elevation view of the Target Pile, including the target, horns and shielding steel.

Radiation Safety Issues (cont.)

- Ground Water Contamination
  - Concentration Model
    - Ground water limits at Dolomite

      for ^{3}H 20pCi/cc/y

      ^{22}Na 0.4pCi/cc/y

The beamline elevation is 721.17 ft

The elevation of the unprotected soil is ~714.60 ft

The elevation of the Silurian Dolomite ~677 ft

Study of soil samples around the MiniBooNE experimental facility [K. Vaziri] show that even after 20 years of continuous operation of the MiniBooNE the concentration of the ^{3}H and ^{22}Na nuclei <<EPA limits.

Conclusions : Ground Water Contamination is not a problem

Radiation Safety Issues (cont.)

- Surface Water Contamination
  - Concentration Model
    - Ground water limits at Dolomite

      for ^{3}H 2000pCi/cc

      ^{22}Na 10pCi/cc

- We need
  - Dual liner system
  - Three sumps
    - inner sump - drain the protected area before Turn-on.
    - Buffer sump - drain buffer zone before Turn-on; test for leakage.
    - Outer Sump - Monitor 3H and 22Na levels in unprotected zone.

Conclusions : Surface water will be monitored.

Radiation Issues (cont.)

- Prompt radiation is of concern only under **Beam-On** conditions. The main contribution is from : **n, μ, γ** produced during interaction.

Dugan's and Don Cossiart's Criteria for MIniBooNE

N_p = 9E16 p /hr

	Over the Magnet	over the beampipe	Burie beam pipe
Prompt Radiation:			
D<1mr/acc.	25.1ft	21.9ft	26.5ft
	(22.7 ft)	(20.7 ft)	(24.7 ft)
D<5 mr/acc.	22.9 ft	19.8 ft	24.3 ft
	(20.5ft)	(18.5ft)	(22.5ft)
D<100mr/acc.	19.1ft	16.1 ft	20.5ft
	(17.2ft)	(16.2 ft)	(18.7ft)
E-Berm :			
2% Beam loss	20.1ft	16.9ft	21.5ft
10%Beam loss	22.21ft	19ft	23.6ft

Physics Prospects

The MiniBooNE has two major Physics Goals

- Neutrino Oscillation Physics
- Non-oscillation Neutrino Physics
  - Neutrino-nucleon elastic scattering and a measurements of Gs

    The $\nu p \text{-->} \nu p$ and $\nu n \text{-->} \nu n$ reactions, where ν is a ν_μ or $\overline{\nu}_\mu$, offer the possibility of extracting Gs, the strange quark axial form factor of the nucleon. (about 72k events are expected) .
  - Neutrino charged-current scattering

    The $\nu_\mu{}^{12}C \text{-->} \mu^{-12}$ N (about 510k events are expected) and $\nu_\mu{}^{12}C \text{-->} \mu^{+12}$ B (about 150k events are expected) will be measured to high precision.
  - Neutral current π^0 production

    The measure of $\nu_\mu C \text{-->} \nu_\mu \pi^o X$ (about 65k events are expected) is a sensitive probe to structure of the weak neutral-current.
  - Neutrino-electron neutral -current scattering

    By measuring the $\nu_\mu e^-$ --> $\nu_\mu e^-$ cross section (about 130 events are expected) we can get infornation on Neutrino-electron neutral -current scattering.

Summary

- Understanding the properties of the neutrinos is an important goal of High Energy Physics.
- Observation of deficits of **solar neutrinos, atmospheric neutrinos and the LSND results** points to possible "**Neutrino Oscillations**"
- MiniBooNE will provide a definitive test of the LSND results and make precision measurements of the oscillation parameters.
- The MiniBooNE experiment has been approved. A preliminary design of the facility is complete.
- Challenges :
  - There are a number of accelerator-related challenges in the Booster to accommodate Run II, MiniBooNE, and NuMI at the same time.
- If neutrino oscillations are observed by MiniBooNE, this will be a major milestone in High Energy Physics.